

# Genetic Trends in Winter Wheat Grain Quality with Dual-Purpose and Grain-Only Management Systems

Iftikhar H. Khalil, Brett F. Carver,\* Eugene G. Krenzer, Charles T. MacKown, Gerald W. Horn, and Patricia Rayas-Duarte

## ABSTRACT

Hard winter wheat (*Triticum aestivum* L.) grain harvested from a dual-purpose (forage plus grain) crop is often perceived by users to have inferior end-use quality compared with that of a grain-only crop. In this paper, we determine if that perception has a scientific basis and if long-term genetic changes in grain quality are equally expressed under two management systems commonly practiced in the southern Great Plains. Uniform trials were established under grain-only and dual-purpose management systems, each featuring whole-plot treatments of a foliar fungicide and split-plot treatments of 12 hard red winter (HRW) wheat cultivars spanning nearly 80 yr of genetic improvement. The study was conducted for 4 yr at the Wheat Pasture Research Center near Marshall, OK. Dual-purpose experiments were grazed from November through late February or early March of each year. Variables measured were kernel hardness, grain protein, flour yield, mixing time and tolerance, large-kernel fraction, kernel weight, and kernel diameter. The effect of fungicide treatment was not significant. Cultivar  $\times$  system interactions were generally absent, and the correlation between management systems varied from  $r = 0.74$  to  $0.99$  ( $P < 0.01$ ), indicating a high level of consistency in quality between systems. Kernel weight in the dual-purpose system did not reach the same level as in the grain-only system for some cultivars, though kernel diameter was not negatively affected. Grain protein and dough strength, measured by mixing time and tolerance, were unaffected by management system. Significant genetic progress was observed in both systems for only the physical quality attributes (kernel weight and diameter, and percent large kernels). With exception of kernel weight, we detected no detrimental effect of the dual-purpose management system on cultivar performance, or on cultivar differences associated with breeding, for several characteristics commonly used to estimate bread wheat quality.

HARD RED WINTER WHEAT is the largest wheat class produced and exported from the USA (USDA, 2000). Much of the crop is produced in the southern Great Plains, where in Oklahoma and surrounding areas, about two-thirds of the wheat hectareage may be used for the dual purpose of forage and grain from the same crop in any given year (Epplin et al., 1998). Depending on moisture availability, dual-purpose wheat is planted usually in late August or early September to supply ample fall forage for grazing from November to early March. Early planting combined with grazing, however, intensifies drought, insect, and disease pressures (Krenzer, 2000; Kelley, 2001; Lyon et al., 2001). Consequently, grain yield may decline in a dual-purpose system, depending on stocking rate or the degree of

defoliation, relative to a grain-only system (Winter et al., 1990; Winter and Thompson, 1990; Winter and Musick, 1991). Estimates of long-term genetic gain for HRW wheat grain yield were reduced significantly under dual-purpose management compared with a grain-only system (Khalil et al., 2002). Associated effects on wheat quality are not documented but are key to our understanding if hard winter wheat is to continue as a world supplier of bread wheat.

Wheat grain harvested from a dual-purpose crop is often perceived to have inferior quality compared with that of a grain-only crop. Several components of bread wheat quality that are central to domestic and international wheat trade are greatly affected by genotype as well as the production environment (Peterson et al., 1998; Guttieri et al., 2000; Marry et al., 2001; Zhu and Khan, 2001). Kernel weight and size, and protein content, may be reduced in the dual-purpose system, possibly because of reduced photosynthetic assimilation and nitrogen available for redistribution during grain filling after forage removal (MacKown and Rao, 1998). Both protein content and composition are critical to several physical characteristics of dough, which, in turn, influence bread volume and texture (Finney et al., 1987).

Several high yielding wheat cultivars have replaced their predecessors during the past decade, but genetic improvement in grain and flour quality has not been evaluated since the report by Cox et al. (1989). In this paper, we describe genetic changes in quality in the context of how they might be influenced by dual-purpose management, a system traditionally not used in the selection of cultivars. Specifically, this study was conducted to: (i) compare selected quality characteristics of wheat harvested from grain-only and dual-purpose management systems, and (ii) compare levels of genetic improvement for quality expressed in the two systems.

## MATERIALS AND METHODS

Field experiments were conducted at the Wheat Pasture Research Center near Marshall, OK, for four consecutive crop seasons from 1997 (harvest year) to 2000. The soil was a fine, mixed, thermic Udic Paleustoll (Kirkland silt loam). Experimental methods were described completely by Khalil et al. (2002) but are repeated here in part for reader convenience. Twelve HRW wheat cultivars (with their assigned year of release)—Turkey (1919), Triumph 64 (1964), Scout 66 (1966), TAM W-101 (1971), Vona (1976), TAM 105 (1979), Chisholm (1983), 2157 (1987), 2163 (1989), Karl 92 (1992), Custer (1994), and 2174 (1997)—were grown in grain-only and dual-purpose management systems in adjacent areas of the pasture. A split-plot treatment design with five replicates was used in each system, wherein foliar fungicide vs. no-fungicide treatments were assigned to whole-plots and the 12 cultivars to subplots. Each subplot consisted of five 3.0-m-long rows spaced 0.23 m apart. For the 2000 experiment, a randomized complete-block design was used with fungicide treatment only, because of the

I.H. Khalil, B.F. Carver, and E.G. Krenzer, Dep. of Plant and Soil Sciences; G.W. Horn, Dep. of Animal Sci.; P. Rayas-Duarte, Dep. of Biochem. and Molecular Biol., Oklahoma State Univ., Stillwater, OK 74078; C.T. MacKown, USDA-ARS, Grazinglands Res. Lab., El Reno, OK 73036. Work supported by USDA-CSREES agreement no. 97-34198-3970 and 99-34198-7481. Published with approval of the Director, Oklahoma Agric. Exp. Stn. Part of a dissertation submitted by I.H. Khalil in partial fulfillment of the Ph.D. degree requirements at Oklahoma State Univ. Received 22 Aug. 2001. \*Corresponding author (bfc@mail.pss.okstate.edu).

Published in Crop Sci. 42:1112–1116 (2002).

absence of fungicide  $\times$  system and fungicide  $\times$  cultivar interactions for grain yield and test weight in the previous 3 yr (Khalil et al., 2002).

As prescribed by Krenzer (2000), the dual-purpose experiments were planted during early to mid-September with a seeding rate of 77 kg ha<sup>-1</sup>, whereas the grain-only experiments were planted during mid-October with a lower seeding rate of 58 kg ha<sup>-1</sup>. The dual-purpose plots were continuously grazed each year from late October or early November until the appearance of hollow stem (early jointing) during late February or early March, determined in ungrazed plants of an early maturing cultivar with the same planting date (Redmon et al., 1996). Grazing duration and average stocking rate were 122 d and 2.30 steer ha<sup>-1</sup> (approximately 651 kg steer ha<sup>-1</sup>) in 1997, 118 d and 2.06 steer ha<sup>-1</sup> (593 kg steer ha<sup>-1</sup>) in 1998, 109 d and 1.65 steer ha<sup>-1</sup> (449 kg steer ha<sup>-1</sup>) in 1999, and 90 d and 1.38 steer ha<sup>-1</sup> (414 kg steer ha<sup>-1</sup>) in 2000, respectively. Other features of the dual-purpose system were described in Khalil et al. (2002). Nitrogen fertilizer (anhydrous NH<sub>3</sub>) was applied according to Oklahoma State Univ. soil-test recommendations to meet the higher requirements of a dual-purpose system. Grain and dry forage yield targets were 3000 and 3500 kg ha<sup>-1</sup>, respectively. Actual amount of applied N varied across years because of adjustment for residual N in the top 60 cm of soil.

All plots of both systems were harvested the same day each year. Immediately preceding harvest, 15 random spikes per plot were collected to determine yield components, from which we estimated 1000-kernel weight. A 200-g grain sample from the bulk harvest of each plot was sifted for 1 min through a Tyler sieve no. 7 (2.80-mm-wide slots) with a Tyler Ro-tap sieve shaker (W.S. Tyler Co., Mentor, OH). Percent large kernels was calculated from the weight of grain retained on the sieve. Mean kernel diameter was determined by means of Perten Single Kernel Characterization System (SKCS, Perten Instruments, Reno, NV).

Quality analyses were performed at the Oklahoma State Univ. Wheat Quality Laboratory by means of procedures similar to those described by Carver (1994). Kernel hardness and grain protein content were determined by near-infrared reflectance (NIR) spectroscopy using a 9-g ground-wheat sample from each plot (method 39-70, AACC, 1995). Hardness index score was measured on a scale of 0 (extremely soft) to 100 (extremely hard). Extraction rate or flour yield was determined in a 125-g grain sample by means of AACC method 12-10A (AACC, 1995), after cleaning and tempering the grain to 155 g kg<sup>-1</sup> moisture and milling on a Brabender Quadrumat senior mill (C.W. Brabender Instruments, South Hackensack,

NJ). Flour yield and grain protein were reported on a 140 g kg<sup>-1</sup> moisture basis. Mixing characteristics were determined with a computer-assisted mixograph (National Manufacturing Co., Lincoln, NE) using a 10-g bowl (method 54-40, AACC, 1995). Mixing time was the number of minutes needed for optimal dough development and was adjusted for flour samples with <120 g kg<sup>-1</sup> protein. Mixing tolerance was rated subjectively on a scale of 1 to 10 based on visual comparison of the mixogram with 10 standard tracings for each of three ranges of flour protein (<10%, 10–13%, and >13%). Scores of 1 to 2 were considered as poor mixing tolerance, 3 to 6 as moderate, and 7 to 10 as strong. Mixing tolerance was also determined as the width of the mixogram curve at 2 min past peak development.

Most attributes were measured in all plots of three replicates for 3 yr (1997, 1998, 1999); kernel weight was measured in all five replicates. Two attributes were added later in the study and were measured only in the fungicide treatment. These were percent large kernels, determined in four or five replicates in 1998, 1999, and 2000, and kernel diameter, measured in either one or three replicates in 1999 and 2000.

Data across years and systems were analyzed by a mixed-effects model. Management systems, fungicide treatment, and cultivars represented fixed effects, whereas replicates and years were considered random. Least significant difference (LSD) values were calculated to compare means for the same cultivar between the two systems, by means of year  $\times$  system  $\times$  cultivar mean squares as the error term. To determine the importance of genetic improvement over time, the cultivar sum of squares in the analysis of variance across years for each system was partitioned into terms presenting linear regression on year of release and deviations from regression. The regression coefficient was considered an estimate of genetic progress for that trait. Heterogeneity of regression coefficients between two systems was based on the significance of system  $\times$  cultivar linear interaction in the combined analysis of variance across years and systems (Khalil et al., 2002).

## RESULTS AND DISCUSSION

The analysis of variance across years and management systems showed significant genetic variation among cultivars for all variables except NIR hardness and grain protein (Table 1). Neither the main effect of management systems nor the interaction of systems with years was significant. Cultivar  $\times$  system interactions were absent, except for kernel diameter, and the correlation

**Table 1.** Summary of selected *F*-tests for physical and chemical grain quality attributes of 12 hard red winter wheat cultivars grown in grain-only and dual-purpose systems at Marshall, OK, from 1997 to 2000.

Source	df	Kernel size			Wheat attributes			Mixograph attributes		
		1000-kernel weight	Large kernel fraction†	Mean kernel diam†	NIR hardness	Wheat protein	Flour yield	Mixing time	Mixing tolerance	Curve width‡
		g	%	mm	1–100	— g kg <sup>-1</sup> —		min	1–10	mm
System (S)	1	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fungicide (F)	1	NS	—	—	NS	NS	NS	NS	NS	NS
S $\times$ F	1	NS	—	—	NS	NS	NS	NS	NS	NS
Cultivar (C)	11	**	**	**	NS	NS	**	*	*	*
S $\times$ C	11	NS	NS	*	NS	NS	NS	NS	NS	NS
F $\times$ C	11	NS	—	—	NS	NS	NS	NS	NS	NS
S $\times$ F $\times$ C	11	NS	—	—	NS	NS	NS	NS	NS	NS
Mean		31.3	58.0	2.2	50.1	127	611	5.1	4.5	12.4
C.V. (%)		9.4	13.4	2.8	25.3	6.8	4.4	14.8	19.6	17.4

\* Indicates *F*-test significant at *P* = 0.05.

\*\* Indicates *F*-test significant at *P* = 0.01.

NS = nonsignificant (*P* > 0.05).

† % large kernels determined in 1998, 1999, and 2000 under fungicide treatment only, and kernel diameter determined in 1999 and 2000 under fungicide treatment only. All other attributes determined in 1997, 1998, and 1999 under fungicide and no-fungicide treatments.

‡ Measured at 2 min past peak development.

between management systems was high for all variables ( $r = 0.74\text{--}0.99$ ,  $P < 0.01$ ). Thus, cultivar differences for a given quality attribute were qualitatively consistent from one system to the other. The main effect of fungicide treatment, and its interaction with other factors, were not significant. Subsequent discussion of cultivar trends is, therefore, derived from means across fungicide treatments.

Kernel weight and diameter are widely used quality indicators in the wheat trade because of their purported influence on wheat milling performance. Hard winter wheat breeders set targets of  $>28$  g for 1000-kernel weight and  $>2.1$  mm for average kernel diameter. Turkey and TAM W-101 showed lowest and highest kernel weights, respectively, in both systems, ranging from 27.0 to 37.4 g in the grain-only system and from 25.6 to 36.2 g in the dual-purpose system (Fig. 1a). System means across all cultivars and years (Table 2) still exceeded the target value of 28 g by about 3 to 4 g. Chisholm and 2163 showed a significant reduction ( $P = 0.05$ ) in the dual-purpose system, whereas no cultivar showed an increase in kernel weight. The moderate correlation between kernel weight and test weight in each system (dual-purpose,  $r = 0.62$ ,  $P = 0.03$ ; grain-only,  $r = 0.55$ ,  $P = 0.06$ ) indicated that kernel weight only partly influenced test weight. Moderate to strong association of kernel weight with test weight was previously reported

for Karl 92 (Gibson et al., 1998) and for several hard winter wheat genotypes (Merkle et al., 1969).

The complete absence of any cultivar showing increased kernel weight under the dual-purpose system contrasted with several cultivars showing increased kernel diameter (Table 2). The two cultivars with significantly lesser kernel weight under the dual-purpose system, Chisholm and 2163, had greater kernel diameter in the dual-purpose system (Fig. 1b), as did five other cultivars (Scout 66, Vona, TAM 105, Custer, and 2174). Increases in kernel diameter in the dual-purpose system could be related to formation of fewer kernels (Khalil et al., 2002) and spikelets per spike (C.T. MacKown, unpublished data). However, mean kernel diameters for the grain-only and dual-purpose systems were similar (Table 2). On a phenotypic basis, kernel diameter was correlated positively with kernel weight ( $r \geq 0.77$ ,  $P < 0.01$ ) in each system. Thus, those cultivars having a genetic tendency toward heavier kernels also had larger kernels. Examples of this association were Triumph 64 and TAM W-101.

International buyers of U.S. HRW wheat place more demand on larger and more uniform kernel size to better assure optimal flour yields (Oades, 1997). In addition to kernel diameter, kernel size also may be measured as the proportion of kernels retained over various wire-mesh screens. All cultivars, except Turkey and Vona, contained a minimum of 50% large kernels in both systems (Fig. 1c). Triumph 64 showed the largest reduction in large-kernel fraction from the grain-only (70%) to the dual-purpose system (59%), but significant changes in other cultivars were not detectable. Hence, the main effect of management system was insignificant (Table 2). The large-kernel fraction was highly correlated among cultivars with 1000-kernel weight, both in the grain-only and dual-purpose systems ( $r \geq 0.85$ ,  $P < 0.01$ ), and with kernel diameter ( $r \geq 0.90$ ,  $P < 0.01$ ). Contemporary

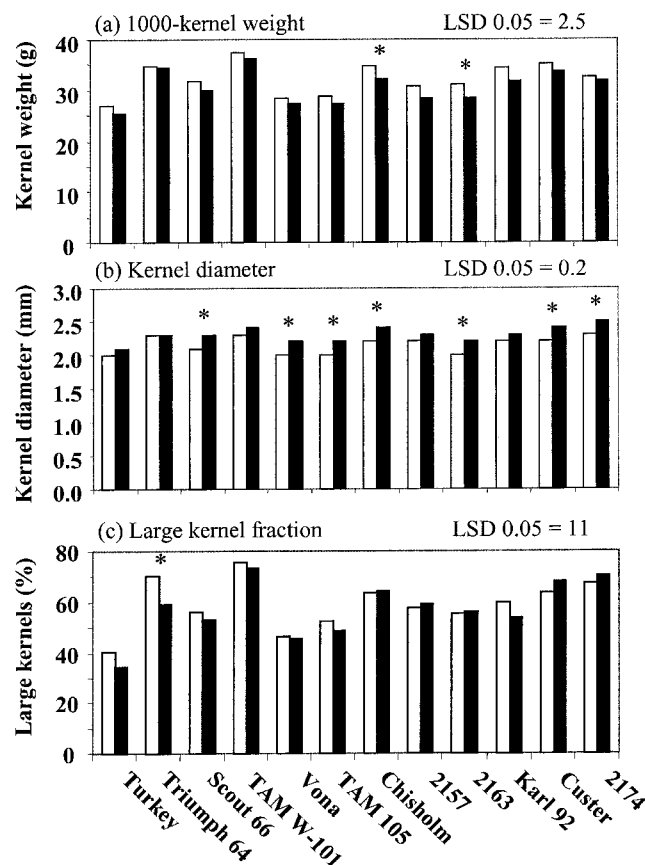


Fig. 1. 1000-kernel weight (a), avg. kernel diameter (b), and percent large kernels (c) of 12 HRW wheat cultivars grown in grain-only (open bars) and dual-purpose (closed bars) systems at Marshall, OK. LSD given for comparing means for the same cultivar between systems. \*Difference between system means  $\geq 1$  LSD value ( $P = 0.05$ ).

Table 2. Means ( $\bar{X}$ ) and regression coefficients ( $b$ ), estimated by linear regression on year of cultivar release, for kernel size and mixograph attributes of 12 hard red winter wheat cultivars grown in grain-only (GO) and dual-purpose (DP) systems at Marshall, OK from 1997 to 2000.

Trait	System	$\bar{X}$	$b^{\dagger}$
1000-kernel weight (g)	GO	32.2	0.06**
	DP	30.5	0.05**
<i>P</i> value		0.11	NS
Large kernel fraction (%)‡	GO	59.0	0.22*
	DP	57.2	0.34*
<i>P</i> value		0.50	NS
Mean kernel diameter (mm)‡	GO	2.16	0.002
	DP	2.29	0.004*
<i>P</i> value		0.23	0.05
Mixing time (min)	GO	5.2	0.01
	DP	5.1	0.01
<i>P</i> value		0.31	NS
Mixing tolerance score (1–10)	GO	4.6	0.006
	DP	4.4	0.003
<i>P</i> value		0.50	NS
Mixogram curve width (mm)§	GO	12.2	0.018
	DP	12.7	–0.003
<i>P</i> value		0.62	NS

\* Indicates significance at  $P = 0.05$ .

\*\* Indicates significance at  $P = 0.01$ .

NS = nonsignificant ( $P > 0.05$ ).

† Comparison of regression coefficients based on significance of system  $\times$  cultivar linear interaction.

‡ Evaluated under fungicide treatment only.

§ Measured at 2 min past peak development.



cultivars did not necessarily have the highest proportion of large kernels. TAM W-101, released 30 yr ago, had heavier kernels and a higher proportion of large kernels in both systems.

Both domestic and international millers prefer wheat grain that produces a high yield of flour. Flour yield may show genetic variation relating to differences in the proportion of endosperm in the kernel (Bergman et al., 1998), and it can be influenced by physical characteristics of the grain, such as kernel weight and size, for which these cultivars had genetic variation (Table 1). Flour yield varied from 595 (Vona) to 631 g kg<sup>-1</sup> (Scout 66) in the grain-only system and from 584 (Chisholm) to 631 g kg<sup>-1</sup> (both Triumph 64 and Karl 92) in the dual-purpose system, with no difference in means ( $P = 0.75$ ) between the grain-only (614 g kg<sup>-1</sup>) and dual-purpose systems (608 g kg<sup>-1</sup>). These values are low compared with commercial extraction rates, but are representative of samples milled on a laboratory-scale flour mill equipped with only one break and reducing roll.

We found no association of flour yield with 1000-kernel weight or large-kernel fraction under either system. For example, TAM W-101 had the highest kernel weight and a high proportion of large kernels both in the grain-only and dual-purpose systems, but its flour yield was 10 to 20 g kg<sup>-1</sup> lower than Turkey's (lowest in kernel weight and large-kernel fraction) in the two systems. A similar trend occurred for Custer. In contrast, Scout 66 and 2157 had relatively low kernel weight and large-kernel fraction but yielded maximum flour across systems (630 and 625 g kg<sup>-1</sup>, respectively). Though a comparable experiment with HRW wheat is lacking, Gains et al. (1997) sieved non-shriveled grains of seven soft wheat cultivars into large, medium, and small kernels. Kernel weight decreased with decreasing kernel size, without any change in flour extraction. Only a moderate level of kernel shriveling, however, significantly reduced flour yield.

All cultivars, other than Turkey, span five former and current breeding programs in the southern Great Plains, but surprisingly, genetic or management system differences were absent for kernel hardness and wheat protein (Table 1). Averaged across cultivars, hardness showed identical scores of 50 in both systems. Wheat protein varied only one percentage unit from 121 (Chisholm) to 132 (Triumph 64 and Scout 66) g kg<sup>-1</sup> under either management system (data not shown), or about 6 to 17 g kg<sup>-1</sup> higher than what is often considered the minimum target value of 115 g kg<sup>-1</sup> for HRW wheat. The two systems averaged 127 (grain-only) and 128 (dual-purpose) g kg<sup>-1</sup> ( $P = 0.87$ ), even though yield performance was influenced by management systems (Khalil et al., 2002). A decrease in wheat protein under the dual-purpose system would have agreed with preliminary observations by MacKown and Rao (1998) and with the greater potential for N deficiency with greater forage production and removal. Our results agree with those reported by Royo and Pares (1996) and Royo and Tribo (1997), who observed no differences in wheat protein content of mechanically clipped dual-purpose and grain-only treatments in barley (*Hordeum vulgare* L.) and triticale (*Triticosecale* Wittm.).

Dough strength, an indication of protein quality, was evaluated by means of mixing time, mixing tolerance score from visual ratings of the mixogram, and mixogram curve width at 2 min past peak development. Commercial bakeries produce best yeast products with a flour having moderate mixing time (3–7 min) and good mixing tolerance (>3, 1–10 scale). Mixing time varied among cultivars from 4.4 to 7.0 min in the grain-only system and from 4.3 to 6.8 min in the dual-purpose system (Fig. 2a), but mixing time did not change between systems (Table 2). Mixing tolerance scores were within the commercially acceptable range in both systems (3–6, Fig. 2b), with no difference between systems (Table 2). Mixogram curve width among cultivars varied from 9.5 to 14.4 mm in the grain-only system and from 10.9 to 15.3 mm in the dual-purpose system (Fig. 2c), also with no difference between system means. Triumph 64 actually had significantly larger curve width in the dual-purpose system (11.9 mm) than the grain-only system (9.5 mm). Mixing time and mixing tolerance may increase with protein content, but such an association did not exist in either system, given the low cultivar variation for wheat protein. Triumph 64 and Karl 92 tended to have highest wheat and flour protein (data not shown) content in both systems, but their mixing times varied by 3 min (4 and 7 min, respectively). The

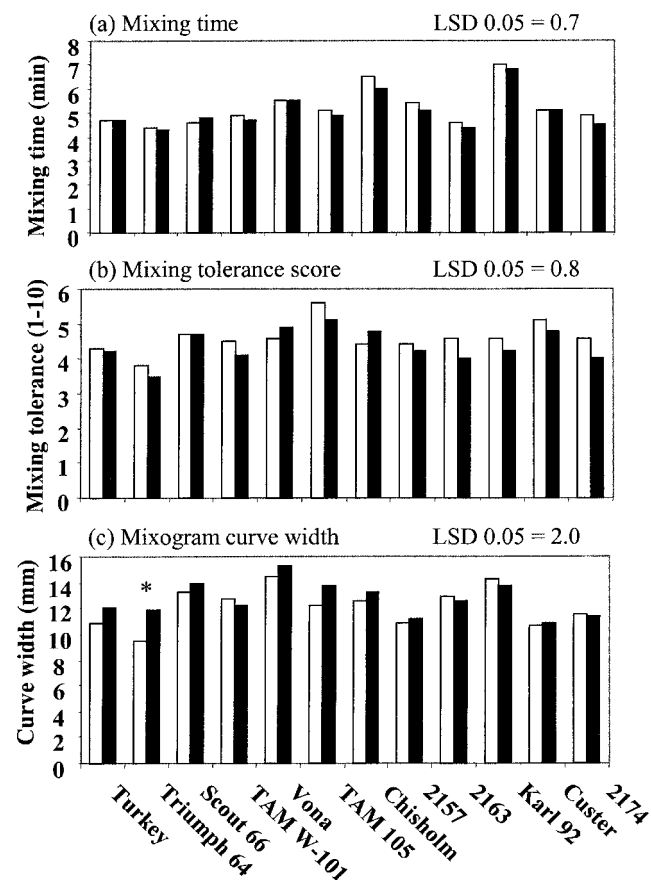


Fig. 2. Mixing time (a), mixing tolerance score (b), and mixogram curve width at 2-min past peak development (c) of 12 HWR wheat cultivars grown in grain-only (open bars) and dual-purpose (closed bars) systems at Marshall, OK. LSD given for comparing means for the same cultivar between systems. \*Difference between system means  $\geq 1$  LSD value ( $P = 0.05$ ).

same disparity was observed for mixing tolerance. TAM 105 tended to have lowest wheat and flour protein ( $109 \text{ g kg}^{-1}$ ) in both systems but had the highest mixing tolerance score (Fig. 2b); however, the reverse was true for Triumph 64. These observations underscore the significance of compositional factors, such as glutenin and gliadin structure, that influence protein functionality.

Genetic selection for improved milling and bread baking characteristics is an integral component of all wheat breeding programs in the southern Great Plains. Selection often takes the form of adopting industry-recommended standards for physical (kernel size and texture) and analytical (dough quality) attributes among breeding lines chosen for superior agronomic potential. Progress in grain yield was previously shown for this set of cultivars, albeit at a reduced level in the dual-purpose system (Khalil et al., 2002). Significant progress was also observed for kernel size attributes, except for kernel diameter in the grain-only system (Table 2). Rates of progress for 1000-kernel weight were  $0.05$  to  $0.06 \text{ g yr}^{-1}$  in both systems, although an older cultivar, TAM W-101, showed the highest kernel weight in both systems. These estimates for kernel weight were similar in magnitude to those reported by Cox et al. (1988). Increases in kernel weight corresponded to significant increases in the large-kernel fraction, with no negative impact of the dual-purpose system. No trends were observed in kernel hardness, protein content, flour yield, or mixograph attributes across time under either system (Table 2). With a larger set of HRW wheat cultivars, Cox et al. (1989) observed a significant increase in flour protein and in mixing time. Despite slight improvements in mean kernel size, flour yield has not substantially increased in HRW wheat (Cox et al., 1989; Peterson et al., 1997) and hard red spring wheat (Souza et al., 1993).

With the exception of kernel weight, we found no obvious detrimental influence of the dual-purpose management system on several characteristics commonly used to describe end-use quality of hard winter wheat. If managed properly for seeding rate and date, grazing initiation and termination, and nitrogen application, this management system should allow the same expression of genetically improved quality traits expected under a grain-only system. Recognizing that actual production practices may depart from those employed in this study, communication among breeders, consultants, growers, handlers, and processors is important for a better understanding of quality expectations following recommended practices.

## REFERENCES

- AACC. 1995. Approved methods of the American Association of Cereal Chemists. Methods 39-70, 12-10A, and 54-40. AACC, St. Paul, MN.
- Bergman, C.J., D.G. Gualberto, K.G. Cambell, M.E. Sorrels, and P.L. Finney. 1998. Genotype and environment effects on wheat quality traits in a population derived from a soft by hard cross. *Cereal Chem.* 75:729–737.
- Carver, B.F. 1994. Genetic implications of kernel NIR hardness on milling and flour quality in bread wheat. *J. Sci. Food Agric.* 65:125–132.
- Cox, T.S., M.D. Shogren, R.G. Sears, T.J. Martin, and L.C. Bolte. 1989. Genetic improvement in milling and baking quality of hard red winter wheat cultivars, 1919 to 1988. *Crop Sci.* 29:626–631.
- Cox, T.S., J.P. Shroyer, Liu Ben-Hui, R.G. Sears, and T.J. Martin. 1988. Genetic improvement in agronomic traits of hard red winter wheat cultivars from 1919 to 1987. *Crop Sci.* 28:756–760.
- Epplin, F.M., R.R. True, and E.G. Krenzer. 1998. Practices used by the Oklahoma wheat growers by region. *Oklahoma Current Farm Econ.* 71:14–24.
- Finney, K.F., W.T. Yamazaki, V.L. Youngs, and G.L. Rubenthaler. 1987. Quality of hard, soft, and durum wheats. p. 677–748. *In* E.G. Heyne (ed.) *Wheat and wheat improvement*. 2nd ed. Agron. Monogr. 13. ASA, CSSA, and SSSA, Madison, WI.
- Gaines, C.S., P.L. Finney, and L.C. Andrews. 1997. Influence of kernel size and shriveling on soft wheat milling and baking quality. *Cereal Chem.* 74:700–704.
- Gibson, L.R., P.J. McCluskey, K.A. Tilley, and G.M. Paulsen. 1998. Quality of hard red winter wheat grown under high temperature conditions during maturation and ripening. *Cereal Chem.* 75:421–427.
- Guttieri, M.J., R. Ahmad, J.C. Stark, and E. Souza. 2000. End-use quality of six hard red spring wheat cultivars at different irrigation levels. *Crop Sci.* 40:631–635.
- Kelley, K.W. 2001. Planting date and foliar fungicide effect on yield components and grain traits of winter wheat. *Agron. J.* 93:380–389.
- Khalil, I.H., B.F. Carver, E.G. Krenzer, C.T. MacKown, and G.W. Horn. 2002. Genetic progress in hard red winter wheat measured under grain-only and dual-purpose management systems. *Crop Sci.* 42:1111–1116 (this issue).
- Krenzer, E.G. 2000. Wheat as forage. p. 27–30. *In* T.A. Royer and E.G. Krenzer (ed.) *Wheat management in Oklahoma*. Oklahoma Coop. Ext. Serv. and Oklahoma Agric. Exp. Stn. E-831.
- Lyon, D.J., D.D. Baltensperger, and M. Siles. 2001. Wheat grain and forage yield as affected by planting and harvest dates in the central Great Plains. *Crop Sci.* 41:488–492.
- MacKown, C.T., and S.C. Rao. 1998. Source-sink relations and grain quality of winter wheat used for forage and grain production. p. 148. *In* *Agronomy abstracts*, ASA, Madison, WI.
- Marry, J.G., J.C. Stark, K. Obrien, and E. Souza. 2001. Relative sensitivity of spring wheat grain yield and quality to moisture deficit. *Crop Sci.* 41:327–335.
- Merkle, O.G., I.M. Atkins, and Tariq-ul-Islam. 1969. Relationships of certain kernel characteristics to test weight in wheat. p. 3–6. *Texas Agric. Exp. Stn. Consolidated Progress Report no. PR-2657-2660*.
- Oades, J.D. 1997. Import wheat buyers: How their quality demands are changing and why. p. 377–381. *In* J.L. Steele and O.K. Chung (ed.) *Proc. Int. Wheat Quality Conf.*, Manhattan, KS. 18–22 May 1997. Grain Industry Alliance, KS.
- Peterson, C.J., R.A. Graybosch, D.R. Shelton, and P.S. Baenziger. 1998. Baking quality of hard winter wheat: Response of cultivars to environment in the Great Plains. *Euphytica*. 100:157–162.
- Peterson, C.J., R.G. Sears, R.A. Graybosch, and D.R. Shelton. 1997. Breeding for quality. p. 175–184. *In* J.L. Steele and O.K. Chung (ed.) *Proc. Int. Wheat Quality Conf.*, Manhattan, KS. 18–22 May 1997. Grain Industry Alliance, KS.
- Redmon, L.A., E.G. Krenzer, Jr., D.J. Bernardo, and G.W. Horn. 1996. Effect of wheat morphological stage at grazing termination on economic return. *Agron. J.* 88:94–97.
- Royo, C., and D. Pares. 1996. Yield and quality of winter and spring triticales for forage and grain. *Grass Forage Sci.* 51:449–455.
- Royo, C., and F. Tribo. 1997. Triticale and barley for grain and for dual-purpose (forage + grain) in a Mediterranean-type environment II. Yield, yield components, and quality. *Aust. J. Agric. Res.* 48:423–432.
- Souza, E., J.M. Tyler, K.D. Kephart, and M. Kruk. 1993. Genetic improvement in milling and baking quality of hard red spring wheat cultivars. *Cereal Chem.* 70:280–285.
- USDA. 2000. *Agricultural Statistics 2000*. U.S. Gov. Print. Office, Washington, DC.
- Winter, S.R., and J.T. Musick. 1991. Grazed wheat grain yield relationships. *Agron. J.* 83:130–135.
- Winter, S.R., and E.K. Thompson. 1990. Grazing winter wheat: I. Response of semidwarf cultivars to grain and grazed production system. *Agron. J.* 82:33–37.
- Winter, S.R., E.K. Thompson, and J.T. Musick. 1990. Grazing winter wheat: II. Height effects on response to production system. *Agron. J.* 82:37–41.
- Zhu, J., and K. Khan. 2001. Effects of genotype and environment on glutenin polymers and breadmaking quality. *Cereal Chem.* 78: 125–130.